Chapter 1. Introduction

1.1 Getting started

The Earth sciences have been united since the late 1960s by the vast body of observations and theory that is known collectively as plate tectonics. In the broadest context, the outer surface of the solid Earth is composed of an interconnected mosaic of large, internally coupled, lithospheric shells. These shells, which are commonly termed plates, resemble the individual pieces of shell on the surface of a cracked egg. Plates are often considered to be rigid, which is an assumption that greatly simplifies the mathematical expression of plate tectonic models while not introducing significant errors in many first-order solutions. The various plates are in constant motion relative to one another, so that each plate is either moving toward, away from, along, or obliquely relative to its boundary with each adjacent plate. The motion of plates is intimately related to the thermal architecture of Earth, as heat is transferred outward from the interior of Earth.

Many Earth scientists have studied relative plate motion since 1965, when the geometric and kinematic aspects of plate tectonics began to be unraveled (Wilson, 1965b; McKenzie and Parker, 1967, 1974; Morgan, 1968; Le Pichon, 1968; Isacks et al., 1968; McKenzie and Morgan, 1969). Models of relative plate motion can generally be divided into two groups: models concerned with how plates move relative to one another at a single instant in time, and models that describe the relative positions of the plates at a series of specific times in the past. Neither of these approaches directly provides a model for the continuous geologic evolution of a plate boundary region. This text+code resource presents a quantitative model that utilizes the present-day relative-motion characteristics of plates in order to describe the continuous motion of one plate relative to another plate over a finite period of time.

1.2 Previous work on relative plate motion

Development of the transform plate-boundary fault idea

The occurrence of vertical faults characterized by strike-slip displacements along the boundaries of mobile continents was recognized by Alfred Wegener (1929, p. 198):

"When the movement of the continental blocks takes place, not perpendicular to the margin (as in eastern Asia), but parallel to it, then the marginal chains can be stripped off by strike-slip faulting, without any sima window appearing between them and the main block. This is basically the same set of phenomena as [previously discussed] for the interior of the continental block, transferred appropriately to the continental margin: If the block moves towards the sima, marginal folding results, in the form of either over-thrusts or stepped folds, according to the direction of movement. If it moves away from the sea floor, the marginal chains split off. But if the movement is in shear, we have strike-slip faulting."

Wegener was unable to trace the extension of subaerial plate-boundary faults into the ocean basins (e.g., Wegener, 1929, Fig. 53), so the early development of the transform fault idea was inhibited. An increased interest in ocean exploration and the application of new technology developed during World War II rapidly led to the discovery of oceanic fracture zones (Menard and Dietz, 1952; Menard, 1959, 1964, 1966, 1967; Heezen and Tharp, 1961, 1964, 1965; Heezen et al., 1961, 1964a, 1964b), faults on the ocean floor (Vacquier, 1959, 1962, 1965; Vacquier et al., 1961; Menard, 1966), discontinuities in seismic character along mid-ocean ridges at faulted ridge offsets (Sykes, 1963), and the spatial relationship of faults and fracture zones to apparent offsets in mid-ocean ridges (Wilson, 1962, 1963a, 1963b; Menard, 1966; Heezen and Tharp, 1964, 1965).

Wilson (1965b) coined the term "transform fault" to describe the strike-slip plate-boundary faults that had earlier been discussed by Wegener (Fig. 1a). Like Wegener before him, Wilson was initially hampered by the paucity of detailed knowledge of the ocean floor, although the basic elements of the transform fault idea were evident in Wilson's earlier writing (e.g., Wilson, 1963a, Fig. 5; Wilson, 1963b). Wilson was able to recognize the significance of great strike-slip faults like the De Geer fault, along the northern boundary of Greenland, as plate-boundary faults between boundaries at which plates were either being created or consumed (Fig. 1b). The proposition that there are three types of plate-boundary environments (convergent, divergent, and strike-slip), all of which can be present along the margins of a given plate, made it easy to visualize the mosaic of mobile plates along the surface of Earth (Wilson, 1962, 1963a).

Of particular importance was Wilson's description of the sense of displacement to be expected across transform faults: "It is significant that the direction of motion on transform faults [between mid-ocean ridge segments] is the reverse of that required to offset the ridge" (Wilson, 1965b, p. 343). Wilson's (1965b) prediction of sense of shear along transform faults was later confirmed by earthquake mechanism studies (Sykes, 1967). In contrast, Menard (1966) typified the earlier hypothesis, that mid-ocean ridges were originally continuous, and had been segmented and offset along transcurrent faults (Fig. 1c). It is an interesting historical point to note that Menard's manuscript was received by the editors of the Journal of Geophysical Research on August 3, 1965, just after Wilson's paper was published in Nature on July 24, 1965.

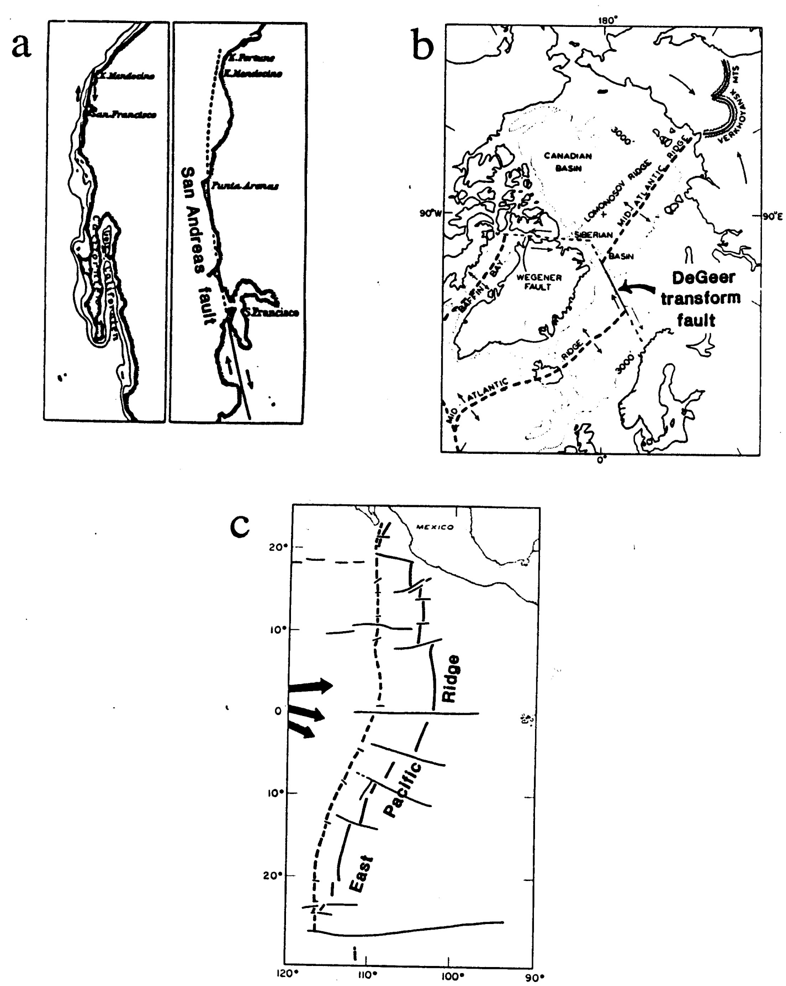

Figure 1. Illustrations chronicling the development of the transform fault idea. (a) Early depictions of the San Andreas fault as a plate-boundary fault. After Webener (1929). (b) Apparent offset of the Mid-Atlantic Ridge along the De Geer transform fault. After Wilson (1965b); similar illustrations had been published earlier (Wilson, 1963a, 1963b). (c) Hypothesis that an initially continuous East Pacific Ridge had been segmented along transcurrent faults with the opposite sense of slip from that predicted by Wilson's transform fault hypothesis (Wilson, 1965b). After Menard (1966).

The small-circle relative-motion model

Quennell (1958) described the motion of Arabia relative to the Sinai as a 6° rotation around an axis located between Crete and Egypt, in what may have been the first use of a rotation to describe the relative motion of lithospheric plates (Girdler, 1985). Wilson (1962, 1963a, 1963b, 1965b) described the motion of the North American plate relative to the Eurasian plate as a rotation around a "fulcrum" located at the northern end of the Verkhoyansk Mountains of Siberia. Similarly, Bullard et al. (1965) used the technique of describing plate motion as a rigid body rotation around an axis through the center of Earth, applying a coordinate transformation theorem by Euler (1776). McKenzie and Parker (1967, p. 1276-1277) also invoked rigid body kinematics to describe relative plate motion in the North Atlantic:

"Transform faults conserve crust and are lines of pure slip. They are always parallel, therefore, to the relative velocity vector between two plates... If one of two plates is taken to be fixed, the movement of the other corresponds to a rotation about some pole, and all relative velocity vectors between the two plates must lie along small circles or latitudes with respect to that pole... If the line of contact [between the two plates] is itself a small circle, then it is a transform fault."

Morgan (1968), Le Pichon (1968), and Heirtzler et al. (1968) utilized similar kinematic reasoning to develop the initial global models of plate tectonics (Fig. 2). Morgan (1968) constructed great circles perpendicular to the strike of several ridge-ridge transform faults for a series of plate pairs in order to estimate the location of the present-day pole of rotation between the two plates. The intersection of all such great circles for a given plate pair was interpreted to be the pole of relative motion. Morgan (1968) observed that the present-day relative pole for the South Atlantic is not coincident with the Eulerian pole around which South America must be rotated in order to achieve the South America-Africa closure predicted by Bullard et al. (1965). This divergence suggested a diachronous relative-motion history (Morgan, 1968). Fox et al. (1969) noted that the shape of the western Kane fracture zone in the north-central Atlantic diverges from a small circle, which was interpreted to signify that the Africa-North America relative pole shifted at ~ 9 Ma.

Cox (1973, p. 40-42) enunciated the two fundamental postulates of modern plate tectonics as follows: "Postulate 1. The plates are internally rigid but are uncoupled from each other"; and "Postulate 2. The pole of relative motion between a pair of plates remains fixed relative to the two plates for long periods of time." Thus, it follows that any given transform fault is a surface of simple shear if the fault trace is a small circle around the pole of relative motion. It also follows that if the relative angular velocity is constant, then the displacement velocity along the transform fault is constant. Finally, the fracture zones that emanate from either end of a given transform fault should form a small circle around the system's pole of relative motion.

Many useful concepts, models, and predictions have been developed based upon the simple kinematic model of plate tectonics whose most important papers were published from 1965 through the early 1970's. A number of good summaries of the history of the development of plate tectonics are currently available (e.g., Tarling and Tarling, 1971; Hallam, 1973; Uyeda, 1978; Glen, 1982; Weiner, 1986). The initial kinematic model of relative plate motion was neatly summarized by Alan Cox (1973) in his basic postulates of plate tectonics, and is herein called the small-circle relative-motion model. Upon close inspection, it can be demonstrated that Postulate 2 and its various corollaries are not generally valid, because relative poles tend to be in motion with respect to the corresponding plates (e.g., Cox, 1973, p. 408; Cox and Hart, 1986, p. 255-258).

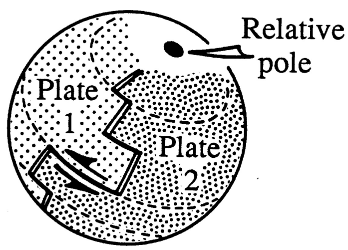

Figure 2. Typical depiction of plate kinematics under the conceptual framework of the small-circle relative-motion model (e.g., Press and Siever, 1986, p. 509). Plate 2 is depicted rotating around the relative pole of the 2-plate system as observed from plate 1 through time. A transform fault is shown as a boundary fault that traces a small circle around the relative pole; hence, there is assumed to be neither convergence nor divergence, only pure strike slip. The fracture zones that emanate from both ends of transform faults are depicted as tracing small circles around the relative pole. The relative pole can therefore be found by fitting small circles to the traces of fracture zones and transform faults.

1.3 Utility of a kinematic model for continuous finite relative plate motion

Understanding relative motion has always been one of the central pursuits of science. Along what path does a projectile move when fired from a cannon? Will the motion of a weather system carry it over a particular city? What can be learned about the configuration of the solar system by studying the complex paths traced by the outer planets? In plate tectonics, the interest lies in understanding how plates move, individually and with respect to one another. This interest arises from the fact that relative plate motion provides the motive force behind many of the significant geological phenomena that occur within the crust of the Earth: earthquakes, volcanic activity, the elevation of mountain ranges as well as the creation of deep ocean troughs, the development of metamorphic and intrusive igneous rock, the concentration of mineral resources, and the folding, faulting, and fracturing of Earth's crust. There is ample economic incentive for gaining a better understanding of relative plate motion, as Earth scientists work to abate potential geologic hazards and search for a variety of economic minerals near plate boundaries.

1.4 Purpose of this document

The purpose of this text+code resource is to provide a general description of quantitative plate kinematics, and specifically to describe the cycloid relative-motion model, which seeks to provide a quantitative model of the kinematics of finite relative plate motion. The first-order version of the cycloid relative-motion model (CYC1) is explained in detail, while higher-order modifications to the cycloid model are suggested. The cycloid model provides a new set of tools to use in synthesizing the geologic evolution of plate boundary zones.

The cycloid model shows that a point on one plate moves along a complex curve as viewed from another plate during a finite time interval. This complex curve can, to the first order, be considered a cycloid. The cycloid is a common relative-motion trajectory for a particle that is rotating around an axis that is, in turn, in motion relative to the observer. Copernicus and Galileo knew the cycloid as the curve traced by the planets as viewed from Earth. The cycloid model of relative plate motion is mathematically similar to kinematic models of relative motion that have been used in other scientific inquiries since the time of Euler.

Initial applications of the cycloid relative-motion model involve the reassessment of conclusions derived by earlier investigators regarding the characteristics of transform faults, fracture zones, triple junctions, and other plate-boundary phenomena that are linked to the finite relative motion of plates. In particular, the following tectonic settings are considered herein in order to display the attributes of the cycloid model more clearly: the Kane transform fault and its fracture zones; the San Andreas fault; a set of long, ridge-ridge transform faults from a variety of plate pairs; the Gulf of California; and the fracture zones of the South Atlantic Ocean. In some applications, the cycloid model suggests explanations for plate-boundary phenomena that had previously been dismissed as local complications. The cycloid model is not only capable of providing answers for some old questions, but it also illuminates a new family of questions that would not have been considered under the earlier conceptual framework.

1.5 References

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